Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2015.1084483

57 (2016) 17255–17261
August

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Taylor & Francis Group

Influence of aeration rate on shortcut nitrification in an SBR treating anaerobic-digested piggery wastewater

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Received 2 December 2014; Accepted 13 August 2015

ABSTRACT

The aeration rate as an intrinsic factor influencing shortcut nitrification process while treating ammonium-rich anaerobic-digested piggery wastewater (ADPW) in a sequencing batch reactor (SBR) was investigated. Diluted ADPW with nitrogen loading rate (NLR) of 0.56 ± 0.12 kg/(m^3 d) was fed to start up the SBR at 0.1 L/min aeration rate. After 24 d of operation, the shortcut nitrification process was established, 71.1% ammonium was removed and a nitrite accumulation rate (NAR) of 96.8% was obtained. Ammonium removal decreased remarkably to 48.6% as raw undiluted ADPW with an NLR of 2.55 kg/(m^3 d) was fed to the system. Intriguingly, aeration rate was raised to 0.4 L/min in the latter feed and an enhanced ammonium removal of 68.9% was observed while NAR decreased to 94.4%.

Keywords: Piggery wastewater; Anaerobic digestion liquor; Sequencing batch reactor (SBR); Shortcut nitrification

1. Introduction

Piggery in China and other developing countries is rapidly expanding into commercial scale as the years come by. This growth trend has led to an increasing generation and discharge of piggery wastewater [1]. The National Bureau of Statistics of the People's Republic of China reported that, about 7.35×10^9 pigs were slaughtered in 2014, which indicated a 2.7% more than that in 2013 [2]. The Statistical data also showed that about 1.1×10^7 tonnes of piggery wastewater were discharged in 2014. Open discharge or disposal of piggery wastewater has a potential health effect and significant adverse effect on the environment since uncontrolled decomposition of waste could lead to epidemic diseases, unbearable foul odors, water eutrophication, and climate change [3–5]. To this effect, discharge standard for the wastewater treatment has been issued in China by the Ministry Environmental Protection of People's Republic of China [6].

Wastewater from piggery varies in quality, mainly due to modes of manure collection [7]. In China, a traditional method of manure collection is done as particulate solid matter (manure) is removed prior to water flushing of the various sites in the piggery. The effluent obtained after flushing is termed as manure-free piggery wastewater and typically has high strength of ammonium with low carbon/nitrogen (C/N) ratio. However, ecological processes and

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1944-3994/1944-3986

advanced biochemical processes are widely accepted as treatment methods in the quest to purifying such wastewater [8–11].

Anaerobic technology has been widely investigated in treating piggery wastewater for its effectiveness in recovering methane gas along with organic pollutant removal [12,13]. However, the anaerobic digested piggery wastewater (ADPW) could not meet discharge standards in China [6], especially in the context of higher concentration of ammonium [14,15]. Ammonium can conventionally be removed by aerobic nitrification and a successive anaerobic denitrification. Herein, this combined process is uneconomical due to its high investment and treatment cost; and waste of land resources [16]. As an alternative, shortcut nitrification–denitrification process compared with traditional nitrification–denitrification via nitrate, has attracted an increasing interest due to its cost-effectiveness [17,18], a 25% reduction in oxygen consumption for nitrification, a 40% reduction in electron donor requirement for denitrification and lesser excess sludge production [19–22].

To develop and maintain shortcut nitrification in wastewater treatment processes, most of which are carried out with sequencing batch reactor (SBR), factors such as dissolved oxygen (DO), temperature, aerating time, and ammonium concentration have extensively been investigated [20,23–28]. DO control is regarded as a promising and practical approach in realizing shortcut nitrification [29,30]. A feasible DO is significant for obtaining shortcut nitrification and this is possible by aeration control in engineering. As illustrated in Eqs. (1) and (2), ammonium would be oxidized to nitrate with excessive aeration, while an incomplete oxidation would occur with insufficient aeration.

$$NH_4^+ + 1.5\,O_2 \;\rightarrow\; NO_2^- + H_2O + H^+ \tag{1}$$

$$NO_2^- + 0.5\,O_2 \;\rightarrow\; NO_3^- \tag{2}$$

A shortcut nitrification process is necessary to the effective treatment of ADPW with high ammonium concentration. As a result, an SBR was constructed and the effect of aeration rate on shortcut nitrification was investigated.

2. Materials and methods

2.1. Reactor and operation

The lab-scale SBR comprised of a cylindrical Plexiglas with its influent intake and mud pipes connected to the conical bottom. The reactor, 12 cm in diameter, stood 35 cm high with an effective working volume of 3.5 L. The temperature (maintained at 28 ± 2˚C) and the aeration rate were controlled with a temperature controller and air flow adjuster, respectively.

Based on previous investigation and another literature reported by Wu and co-workers [31,32], a 6-h cycle time was applied to the operation of the SBR; 5-min instant fill, 5-h aeration, 30-min settling, and 25-min effluent discharge. The feed and discharged volumes per cycle were both 2.5 L. Supplementary oxygen necessary for ammonium oxidation typically depends on DO of the wastewater which subsequently also depends on the aeration rate. In order to control DO in the SBR to about 0.8, 1.5, 2.0, and 2.5 g/L, the respective aeration rates were introduced (0.1, 0.1, 0.2, and 0.4 L/min) [22,33]. The SBR operated for 63 d and its performance was categorized into four stages based on the aeration and nitrogen loading rates (NLRs). The control parameters for each stage are illustrated in Table 1. The sludge retention time (SRT) was kept at 13 d by discharging excess sludge throughout the performance.

2.2. Feed and inoculum

The feed was ADPW collected from an up-flow anaerobic sludge bed (UASB) reactor treating raw piggery wastewater and its characteristics are as summarized in Table 2.

Aerobic activated sludge collected from an aeration tank treating ADPW was used to inoculate the SBR. The inoculated sludge in the SBR was 2.48 g/L in terms of suspended solid (SS).

2.3. Analytical methods

Samples taken during the entire duration of the experiment were analyzed for chemical oxygen demand (COD), biological oxygen demand (BOD_5), ammonium (NH_4^+-N), nitrite (NO_2^--N), and nitrate (NO_3^--N) in accordance with Standard Methods [34]. DO and pH were measured with a dissolved oxygen meter (HANNA, HI2400) and a pH meter (Shanghai Rex, PHS-3c), respectively. The total nitrogen (TN) estimate was derived from the summation of NH_4^+-N, NO_2^--N, and NO_3^--N, while nitrite accumulation rate (NAR) was obtained by the relation below [35].

$$NAR = NO_2^-\text{-N}/(NO_2^-\text{-N} + NO_3^-\text{-N}) \times 100\%$$

where NO_2^--N and NO_3^--N are nitrite and nitrate concentration in effluent, respectively.

Table 1
Operational stage and their control parameters

Stage	Aeration rate (L/min)	Time (d)	Temp. (℃)	Aeration time (h)	Average DO (g/L)	NLR[a] (kg/(m^3 d))	OLR[b] (kg/(m^3 d))
1	Startup (0.1)	24	28 ± 1	5	0.82 ± 0.06	0.56 ± 0.12	1.88 ± 0.42
2	0.1	13	28 ± 1	5	1.53 ± 0.06	2.18 ± 0.19	2.53 ± 0.47
3	0.2	13	28 ± 1	5	2.00 ± 0.08	2.09 ± 0.11	2.54 ± 0.24
4	0.4	13	28 ± 1	5	2.50 ± 0.04	2.20 ± 0.10	2.55 ± 0.50

[a]Nitrogen loading rate.
[b]Organic loading rate in terms of COD.

Table 2
Characteristics of the feed

	NH_4^+-N (mg/L)	NO_3^--N (mg/L)	NO_2^--N (mg/L)	COD (mg/L)	pH
Startup stage	104.26–162.19	0.63–3.70	0.96–13.90	352–596	7.7–8.2
Other stages	502.16–590.98	1.02–3.63	1.08–2.43	507–744	8.4–8.6

3. Results

3.1. Reactor start-up

ADPW with an NLR of 0.56 kg/(m^3 d) was fed to the inoculated reactor (2.48 gSS/L) and an aeration rate of 0.1 L/min was introduced. As shown in Fig. 1(A), an abrupt increase of 140 mg/L NH_4^+-N in the effluent was observed in the first 4 d, but the reverse (decrease) in the subsequent 4 d. However, effluent concentration of NH_4^+-N remained steady 9th day onwards and an average removal rate of 71% was encountered during the last 15 d. Though disintegration of anaerobic bacteria in the ADPW made effluent TN slightly higher than that of influent [16], this resulting behavior was inconsistent. The resultant TN, NO_2^--N, and NO_3^--N in the effluent showed a steady phenomenon just as that in NH_4^+-N (Fig. 1(B) and (C)). However, COD concentration and its removal from effluent varied until day 11–24 (Fig. 1(D)) where a stable result was obtained to reach an average removal of 71.1 and 51.5%, NH_4^+-N and COD, respectively. The lower TN removal of 1.3% (Fig.1(B)) and the higher NAR of 96.8% (Fig.1(C)) indicated that shortcut nitrification occurred very well in the reactor [30].

Effluent pH dropped to 6.4 on day 9 (Fig.1(E)), following NH_4^+-N oxidation and its corresponding increase in NO_2^--N. However, in the stable period (day 11) where COD and NH_4^+-N removal were consistent, an averaged effluent pH of 7.0 was obtained with respect to the stability although influent pH was about 7.9. This alkalescent condition contributed to the 96.8% NAR in the SBR [36].

3.2. Effect of aeration rate on shortcut nitrification

With an average NLR of 2.15 kg/(m^3 d) and organic loading rate (OLR) of about 2.55 kg/(m^3 d), an investigation was carried out on the effect of aeration rate on shortcut nitrification shortly after SBR start-up. The aeration rate per each stage varied increasingly from 0.1 to 0.4 L/min (Table 1). After 5 d of operation (stage 2) with an aeration rate of 0.1 L/min, the SBR attained a steady state where NH_4^+-N, TN, COD, and BOD_5 removals yielded 48.6, 24.0, 45.9, and 70.7%, respectively (Fig. 2). Within the steady process (6th–13th day), an averaged NAR of 96.8% with a pH of 8.0 was observed.

Similarly, in stages 3 and 4 having an aeration rate of 0.2 and 0.4 L/min, respectively, the SBR reached a steady state again after 5 d. COD, BOD_5, and NH_4^+-N removal averaged 51.8,73.5, and 61.8%, respectively, within the steady process (18th–26th day) of stage 3, but increased further to 52.6, 75.7, and 68.9%, respectively (31th–39th day), in stage 4. The NAR was about 96.6% in stage 3 and 94.4% in stage 4, with a TN removal of 19.3 and 13.9%, respectively. The pH markedly decreased to about 7.5 and 6.9 at aeration rate of 0.2 L/min, respectively, due to the accumulation of NO_2^--N.

4. Discussion

As shown in Fig. 2, the SBR attained a steady state in 5 d after aeration rate was increased. Performance in NH_4^+-N and COD removal efficiency in each steady state illustrated in Table 3 show that the average

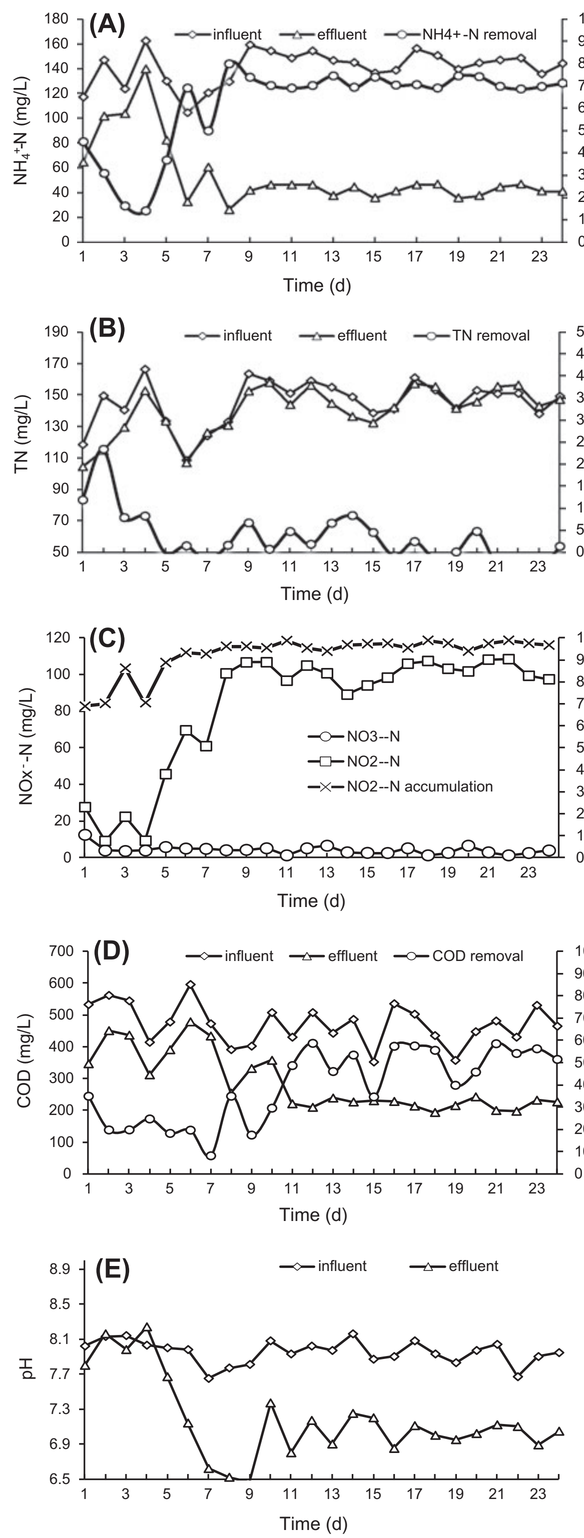

Fig. 1. Performance of SBR in the start-up stage.

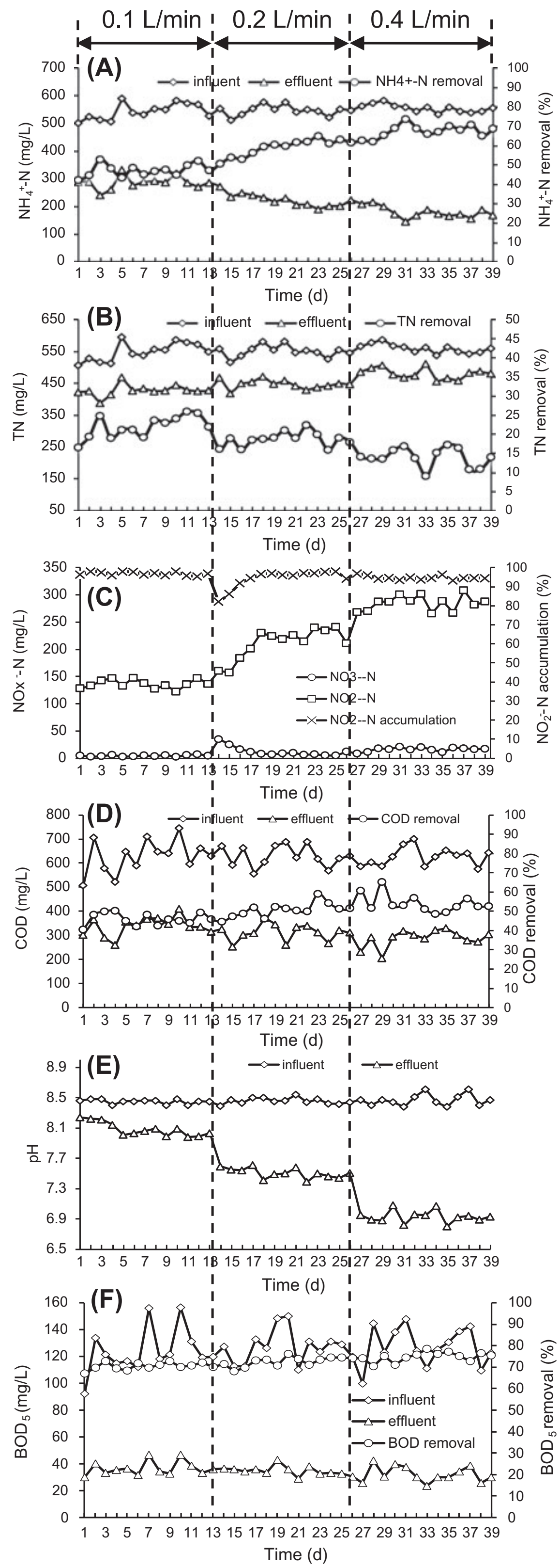

Fig. 2 Performance of SBR at the aeration rate of 0.1, 0.2, and 0.4 L/min.

Table 3
The comparison of shortcut nitrification in SBR at different aeration

Item		Stage 2[a] (AR[b] 0.1 L/min)	Stage 3[a] (AR[b] 0.2 L/min)	Stage 4[a] (AR[b] 0.4 L/min)
NH_4^+-N	In (mg/L)	558.0 ± 22.6	552.0 ± 17.1	549.2 ± 9.9
	Out (mg/L)	288.1 ± 26.2	212.8 ± 26.2	170.3 ± 14.5
	Removal (%)	48.6 ± 3.9	61.8 ± 1.7	68.9 ± 2.6
TN	In (mg/L)	563.9 ± 20.2	554.8 ± 17.3	553.1 ± 9.8
	Out (mg/L)	428.4 ± 24.6	447.4 ± 12.2	476.2 ± 17.0
	Removal (%)	24.0 ± 3.9	19.3 ± 1.8	13.9 ± 2.9
NO_2^--N	In (mg/L)	1.3 ± 0.2	1.6 ± 0.2	1.8 ± 0.5
	Out (mg/L)	135.7 ± 8.2	226.9 ± 10.8	288.0 ± 14.8
NO_3^--N	In (mg/L)	2.7 ± 0.6	1.8 ± 0.6	2.3 ± 0.3
	Out (mg/L)	4.5 ± 1.6	7.8 ± 2.2	17.2 ± 3.0
NAR (%)		96.8 ± 1.0	96.6 ± 1.1	94.4 ± 0.9
COD	In (mg/L)	651 ± 49	634 ± 40	637 ± 39
	Out (mg/L)	353 ± 27	317 ± 36	301 ± 19
	Removal (%)	45.3 ± 2.4	51.8 ± 3.5	52.6 ± 2.8
BOD_5	In (mg/L)	127 ± 16	129 ± 12	128 ± 13
	Out (mg/L)	37 ± 5	34 ± 4	31 ± 5
	Removal (%)	70.7 ± 1.4	73.5 ± 1.7	75.7 ± 1.6
pH	In	8.4 ± 0.0	8.5 ± 0.0	8.5 ± 0.1
	Out	8.0 ± 0.0	7.5 ± 0.1	6.9 ± 0.1

[a]The data in the table are the average values of each stationary phase, and NAR is short for nitrite accumulation ratio.
[b]The aeration rate.

removal rate of NH_4^+-N increased from 48.6 to 61.8% but was further increased to 68.9% as aeration rates were increased from 0.1 to 0.2 L/min and 0.4 L/min, respectively. On the contrary, TN removal rate decreased from 24.0% to the range of 19.3–13.9% stage by stage. The aeration rate increments resulted in an enhanced nitrification but rather inhibited denitrification. This phenomenon potentially was the reason for the increasing removal of NH_4^+-N and the decreasing removal of TN [37].

NAR in each steady state with pH ranging between 6.9 and 8.0 yielded about 94%, indicating a satisfactory performance of the shortcut nitrification process in the SBR [38]. The SRT around 13 d also contributed immensely in obtaining the shortcut nitrification [22]. Autotrophic micro-organism (ammonia oxidizing bacteria—AOB) growth is too slow to contest with the heterotrophic microbes in an aerated condition for ample supply of BOD_5, the nitrification process is inhibited [39,40]. So the biodegradable organics in terms of BOD_5 had the tendency to affect the oxidation of NH_4^+-N. In this paper, nitrification could be found only when BOD_5 was consumed. As illustrated in Table 3, BOD_5 in influent was about 128 mg/L but decreased to about 34 mg/L after aerating for 5 h. The consumption of BOD_5 made AOB active in the SBR, resulting in a high NAR above 94%.

It has been reported that the NH_4^+-N removal is achieved mainly by being oxidized to NO_2^--N and NO_3^--N successively [41,42], and AOB is more powerful in contending for DO than nitrite oxidizing bacteria (NOB) [43]. However, more NO_2^--N would be oxidized to NO_2^--N when oxygen supplement is in excess, resulting in a decrease in NAR [43]. Thus, NAR in the SBR decreased slightly from 96.8 to 96.6% and to 94.4% as aeration rate was increased from 0.1 to 0.2 and to 0.4 L/min, respectively.

Though the results (Table 3) show that aeration rate 0.4 min/L was optimum for shortcut nitrification, the shortcut nitrification should be maintained at a lower aeration rate. According to the data illustrated in Table 3 and Eq. (1), BOD_5 for the biodegradable organics was about 0.09, 0.10, and 0.10 g/L, while the theoretical oxygen demand for NH_4^+-N oxidation was 0.70, 0.90, and 1.00 g/L in the three steady states, respectively. The respective total oxygen demand amounted to 0.80, 1.00, and 1.11 g/L. Obviously, DO in the three stages was in excess (Table 1). In view of the effluent abound with NH_4^+-N, a longer aeration time or SRT is suggested to enhance shortcut nitrification. The enhancement could also be achieved by developing aeration system to improve oxygen transfer efficiency. Furthermore, it is suggested that a subsequent SBR should be used to obtain a better TN removal by shortcut denitrification [44].

5. Conclusion

An SBR with OLR of about 1.88, 0.56 kg/(m^3 d) NLR, 0.1 L/min aeration rate, and a 5 h aeration time were used as operational conditions during the reactor's start-up. This was carried out to aid the development of a shortcut nitrification process during treatment of ADPW. Shortcut nitrification could be established within 24 d in the SBR. The aeration rate had an obvious influence on NAR, NH_4^+-N and TN removal. With an optimal aeration rate of 0.4 min/L, obtained NAR and NH_4^+-N removal in the SBR were 94.4 and 68.9%, respectively. An SBR–SBR process was suggested to construct shortcut nitrification–denitrification for removing nitrogen efficaciously from the ADPW.

Acknowledgements

The authors thank the National Natural Science Foundation of China (Grant No. 51178136), the Major Science and Technology Program for Water Pollution Control and Management (Grant No. 2013ZX07201007), the Science and Technology Department of Heilongjiang Province (Grant No. GC13C303), and the State Key Laboratory of Urban Water Resource and Environment, Harbin Institute of Technology (Grant No. 2013DX11) for valuable financial support.

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